

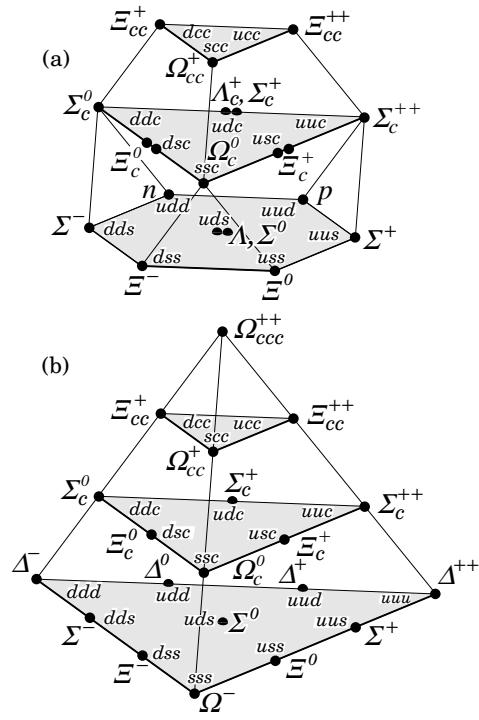
Charm Particle Observations in SELEX

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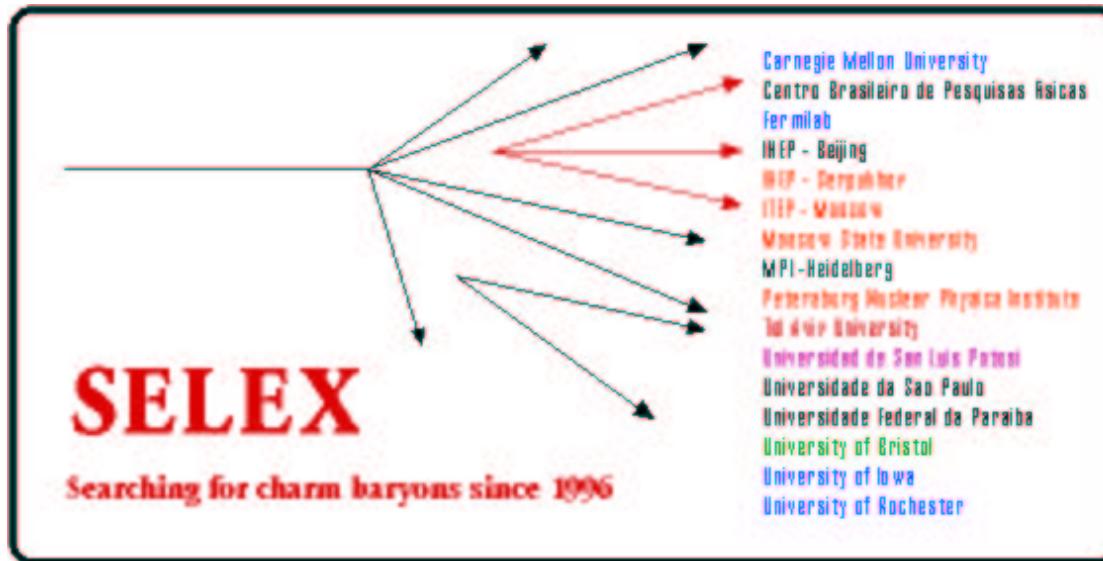
*FPCP 2004
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Outline

- The SELEX Fermilab E781 Experiment
- SELEX Single-Charm Baryon Snap Shot
- Double-Charm Baryon Ξ_{cc}
- Charm Strange Meson $D_{sJ}(2632)$
- Summary and Perspective



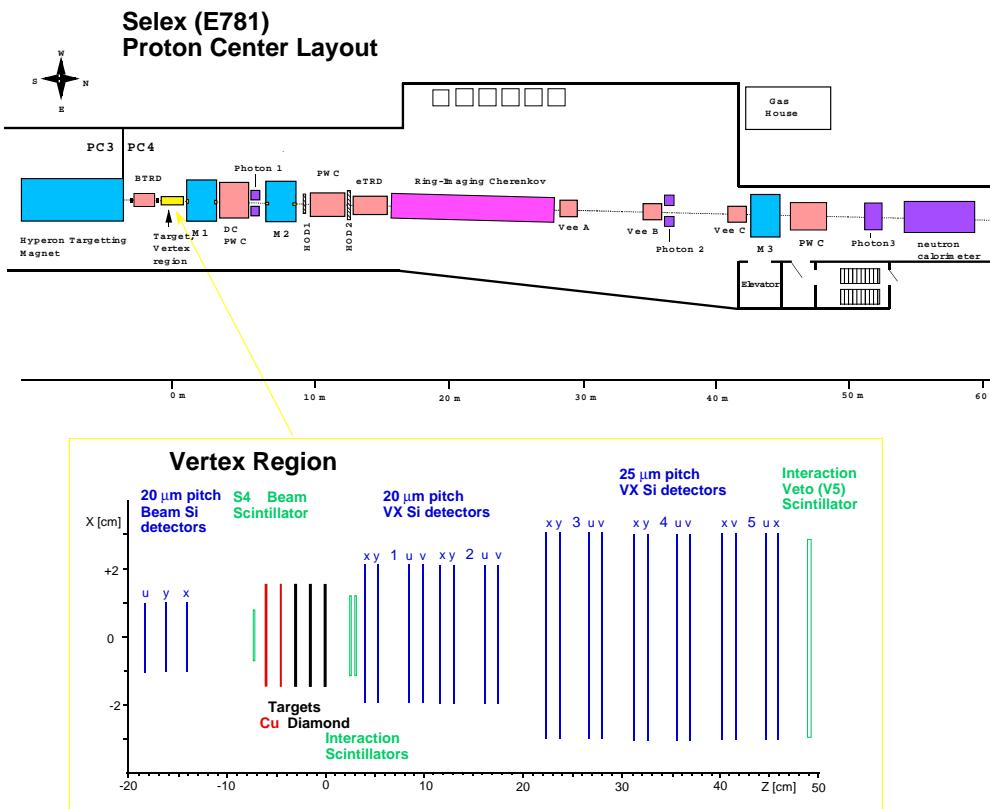
SELEX, Fermilab E781 Experiment



Segmented Large x_F Baryon Spectrometer

- Unique hadro-production with small p_T and large x_F
- Took data during the 1996-97 fixed target run at Fermilab
- 1×10^9 events with 600 GeV Σ^- , π^- and 540 GeV p beams.
- Charm Physics Program
 - Production
 - Decay Physics
 - Spectroscopy

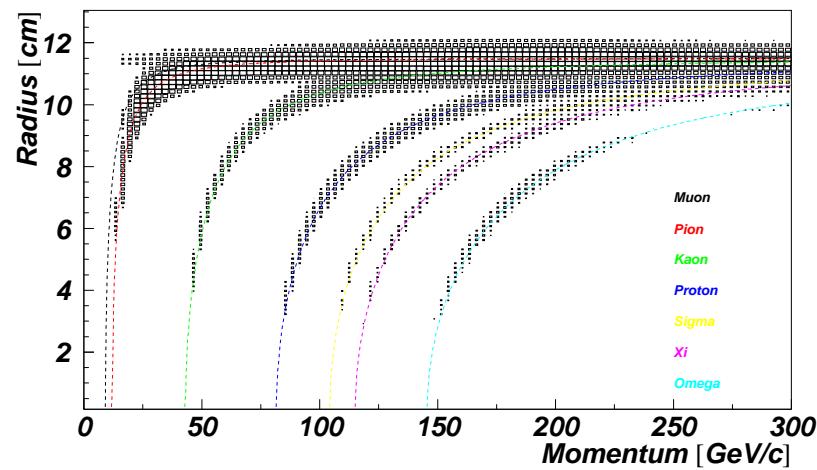
SELEX Apparatus Features



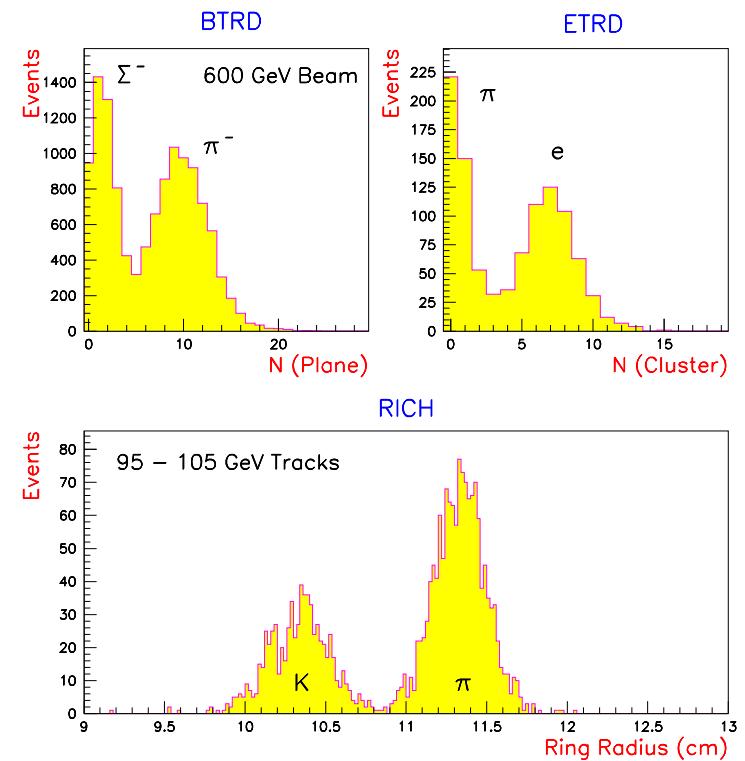
- Typical Lorentz Boost ~ 100

- Segmented targets (2 Cu and 3 C)
- Silicon Vertex Detectors
 $\sigma = 4\mu\text{m}$ @100GeV
- Particle Identification
 - Beam TRD and Electron TRD
 - Ring Imaging Čerenkov Detector
 - Lead Glass Photon Detectors
- Analyzing magnets (M1-M2-M3)
- Downstream Tracking
 $\Delta p/p \sim 0.5\%$ for 100 GeV
 - 18 large silicon planes ($\sigma \sim 8\mu\text{m}$)
 - 26 PWC and 3×24 VDC

Charged Particle Identification



Particle ID: μ , π , K , p , Σ , Ξ , Ω

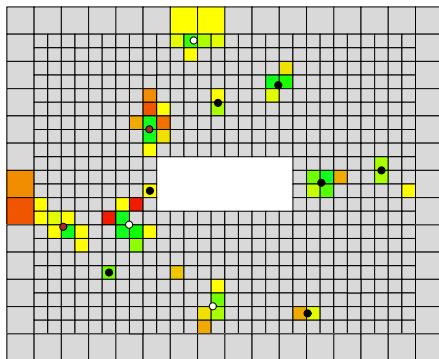


- **RICH**

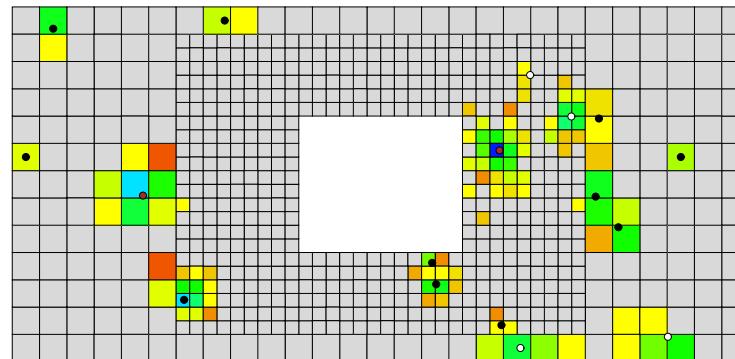
- $\sigma(\text{Ring Radius}) = 1.56 \text{ mm}$
- $2\sigma K/\pi$ separation upto 165 GeV
- $\epsilon(p) > 95\%$ $P_p \approx 90 \text{ GeV}/c$
- π Mis-identification Rate $\sim 4\%$

Lead Glass Photon Calorimeters

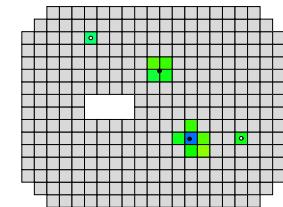
Photon1 ($1 < E_\gamma < 10$)



Photon2 ($2 \text{ GeV} < E_\gamma < 40 \text{ GeV}$)



Photon3 ($4 < E_\gamma < 80$)

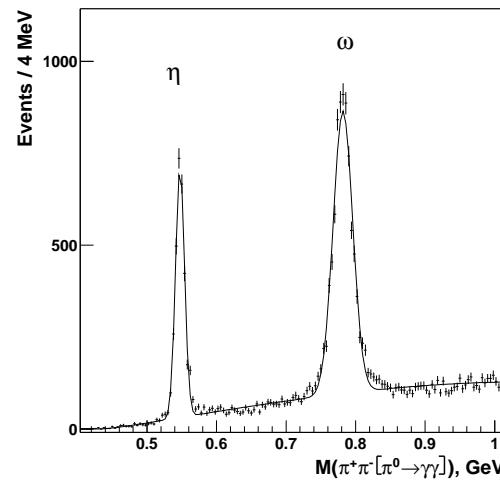
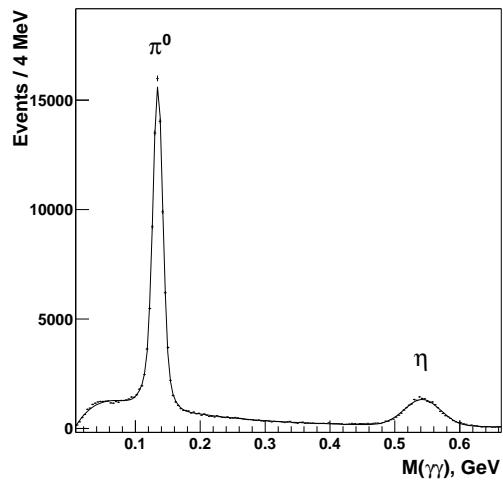


2π coverage in c.m. of primary interaction

Photon energy calibration with special runs ($N_{trk} \leq 5$)

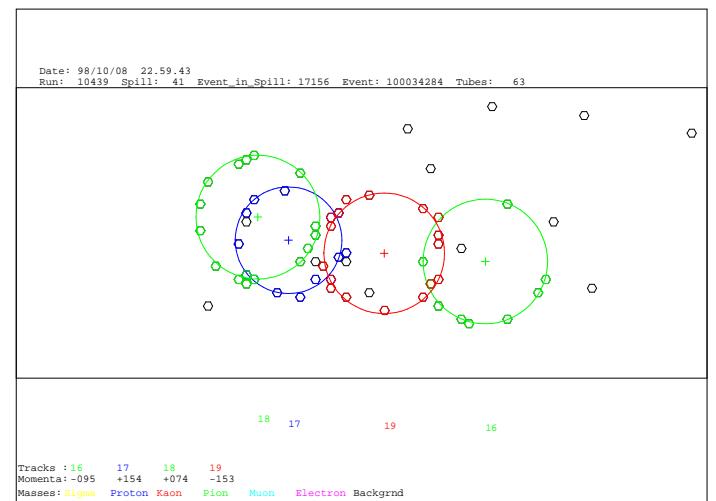
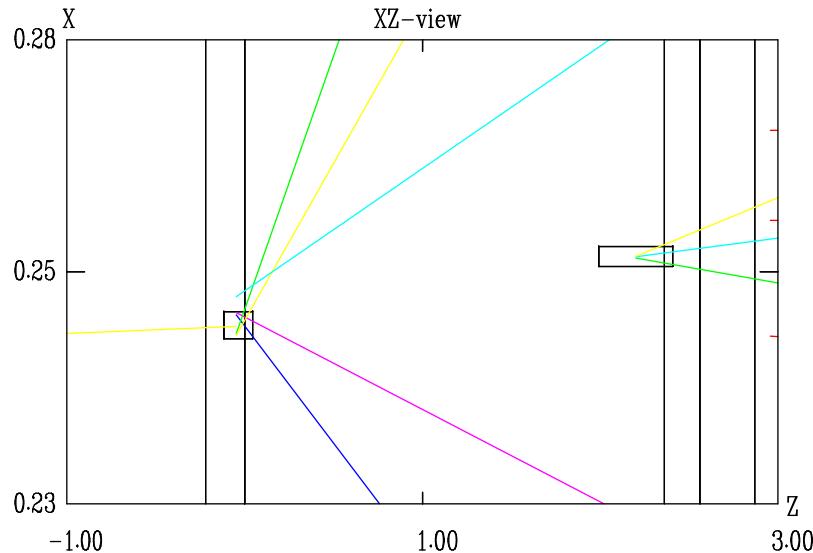
$\gamma\gamma$

$\pi^+\pi^-\pi^0$



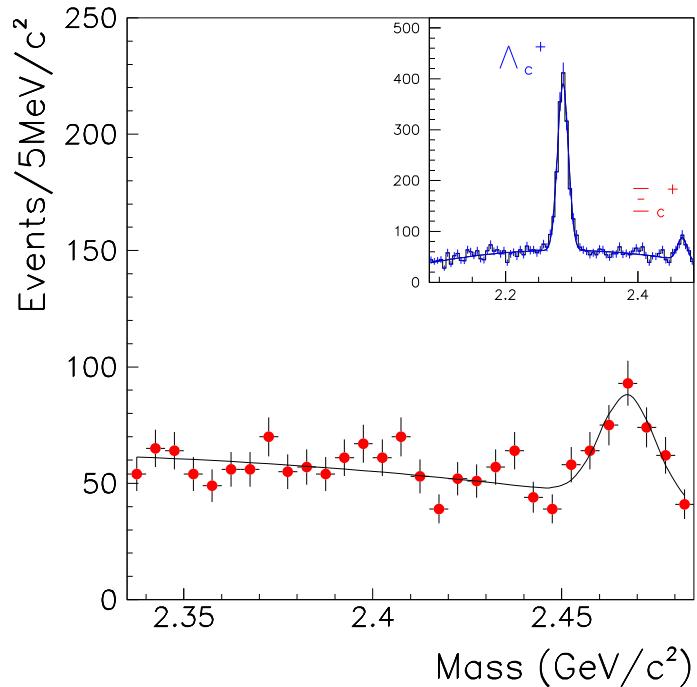
Photon energy scale uncertainty $< 2\%$

SELEX Single Charm Analysis

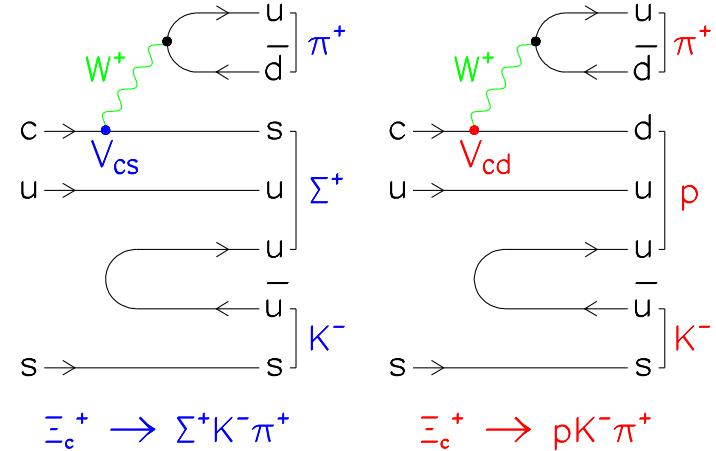


- primary vertex tagged by beam track
- 3D decay vertex must lies outside material
- RICH identification whenever possible
- decay vertex separation significance (L/σ)
- charm vector points back to primary (b/σ_b)
- 2nd largest miss significance among decay track ≥ 4

Observation of $\Xi_c^+ \rightarrow pK^-\pi^+$ PRL 84, 1857(2000)



- Signal Events = $150 \pm 22 \pm 5$ @ $M_{\Xi_c^+} = 2467.4 \pm 1.2$ (MeV/c²)
- Confirmed by FOCUS
PL B512, 277 (2001)



$$\Gamma \propto G_F^2 \sum_{q=d,s} |V_{uq} V_{cq}|^2 \mathcal{F}(m_Q)$$

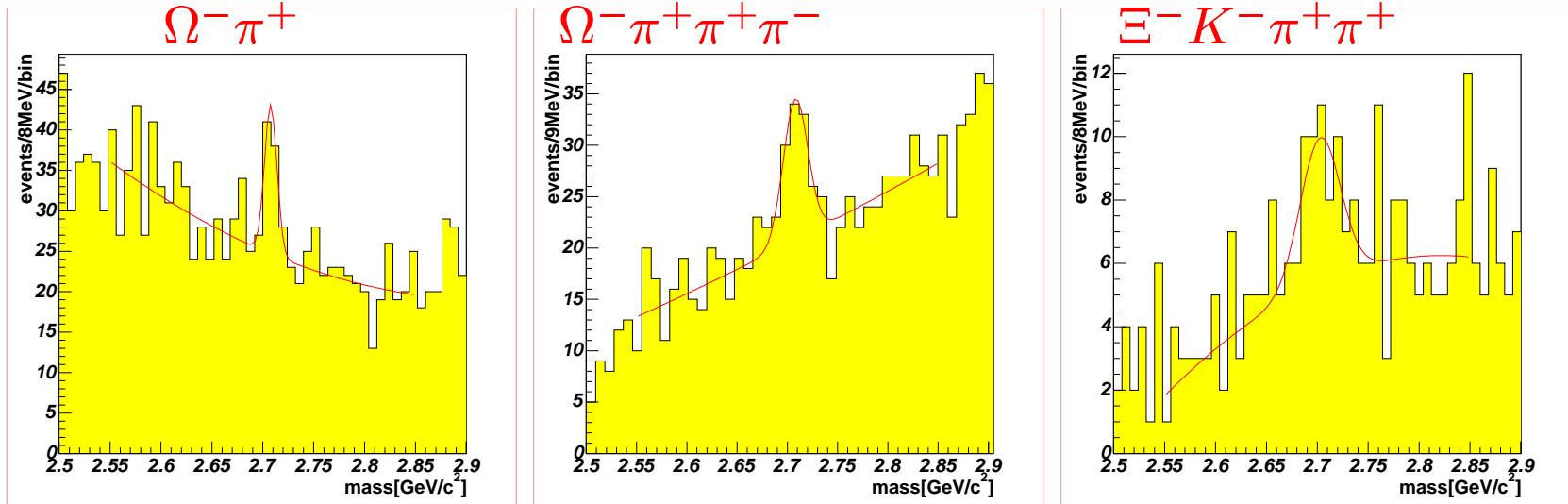
$$\frac{\Gamma_{CS}}{\Gamma_{CF}} \approx \mathcal{O}\left(\left|\frac{V_{cd}}{V_{cs}}\right|^2 = \tan^2 \theta_c\right)$$

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^+ K^-\pi^+)} = 2.1\alpha \times \tan^2 \theta_c$$

$$\alpha = 2.0 \pm 0.5 \pm 0.2$$

Heaviest Single Charm Baryon Ω_c^0

- Limited Ω_c^0 worldwide statistics: E687(42), CLEO(40), BELLE(24), FOCUS(64)
- A tighter RICH PID on daughter $K^- (\pi^-)$ in $\Omega^- (\Xi^-)$



Ω_c^0	Mass (MeV/c ²)	Signal
$\Omega^- \pi^+$	2707.1 ± 2.4	35 ± 12
$\Omega^- \pi^+ \pi^+ \pi^-$	2708.0 ± 4.5	44 ± 14
$\Xi^- K^- \pi^+ \pi^+$	2702.8 ± 8.0	28 ± 12
SELEX Average	$2706.5 \pm 2.1 \pm 1.2$	107 ± 22

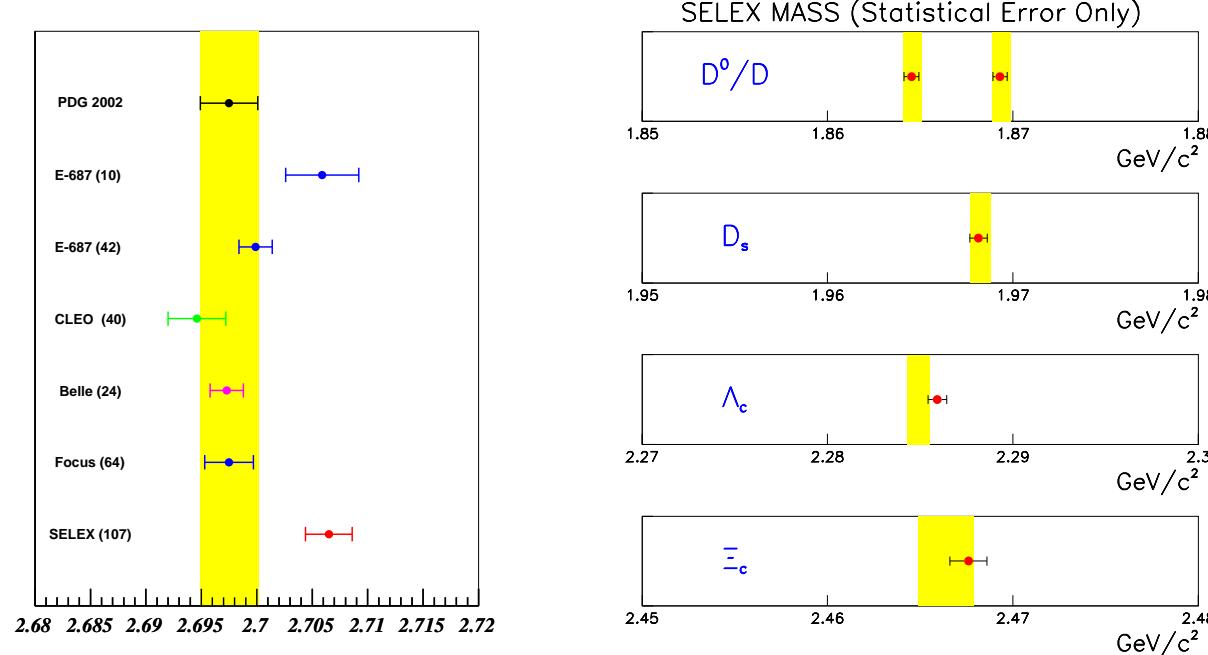
World Average Ω_c^0 Mass = 2697.5 ± 2.6 (PDG2004)

Ω_c^0 Properties

- Preliminary Lifetime: $\tau(\Omega_c^0) = (74 \pm 16)$ fs [(69 ± 12)fs (PDG2004)]
- Relative Branching Fraction

$$\frac{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \pi^+ \pi^+ \pi^-)}{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \pi^+)} = 2.13 \pm 0.45 \pm 0.30$$

- Production extends to large x_F (leading particle effect by Σ^- beam)
- SELEX Ω_c^0 mass: 2.7σ from PDG2004
all other meson/baryon measurements are consistent with PDG2004



Double Charm Baryon

- ccq ($q = u, d, s$) is a good probe of structure of baryons
- QQq system similar to $\bar{Q}q$ meson or $Q\bar{Q}$ quarkonium
- Simplest mass estimation

$$ccu = csu + (csu - ssu) = 2 \cdot \Xi_c^+ - \Xi^0 = 3618 \text{ MeV}$$

- Sampling of ccq mass predictions (GeV/c^2)

author	year	model	$\Xi_{cc}(\text{J} = 1/2)$	$\Xi_{cc}(\text{J} = 3/2)$
Bjorken	1986	phenom	3.64	3.70
Fleck & Richard	1989	bag	3.516	3.636
Fleck & Richard	1989	quarkonium	3.613	3.741
Roncaglia <i>et al.</i>	1995	Feynmann/Hellman	3.66	3.81
Ellis	2002	phenom	3.651	3.711

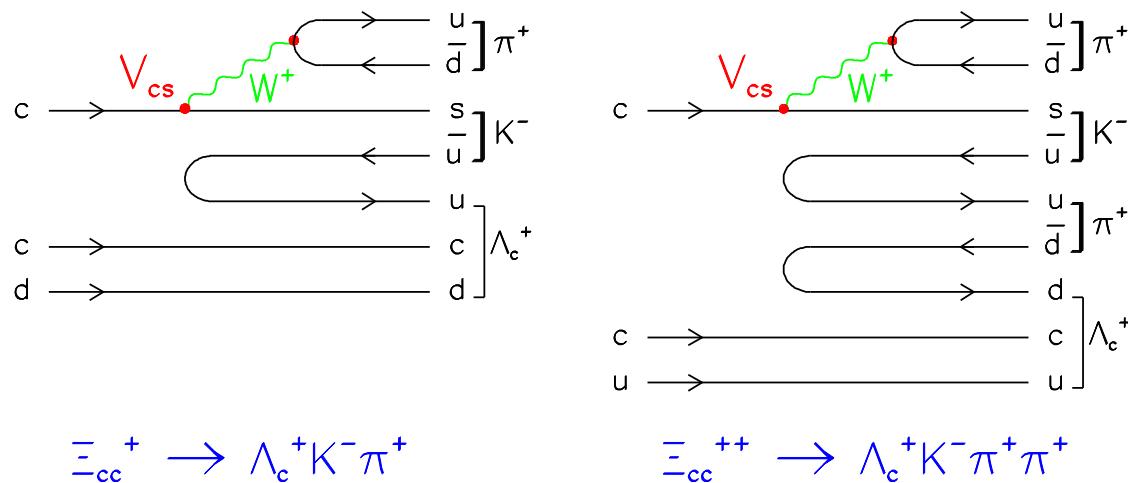
ground state near $3.6 \text{ GeV}/c$
hyperfine splitting around $60\text{-}120 \text{ MeV}/c^2$

Nomenclature and Spectator Diagrams for Ξ_{cc} Decays

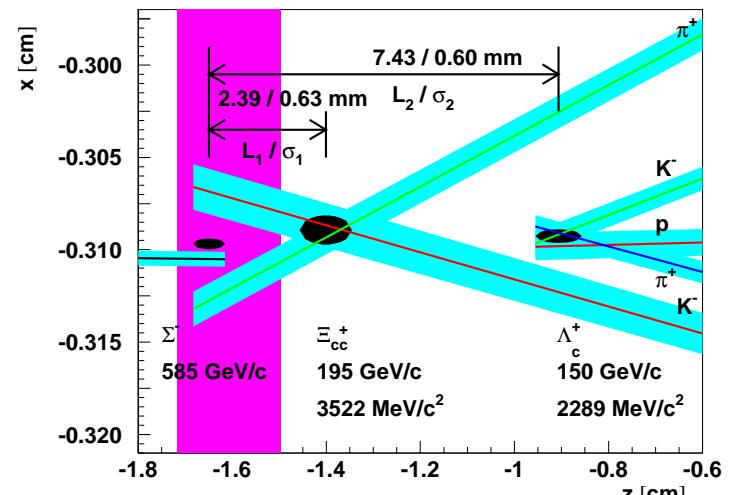
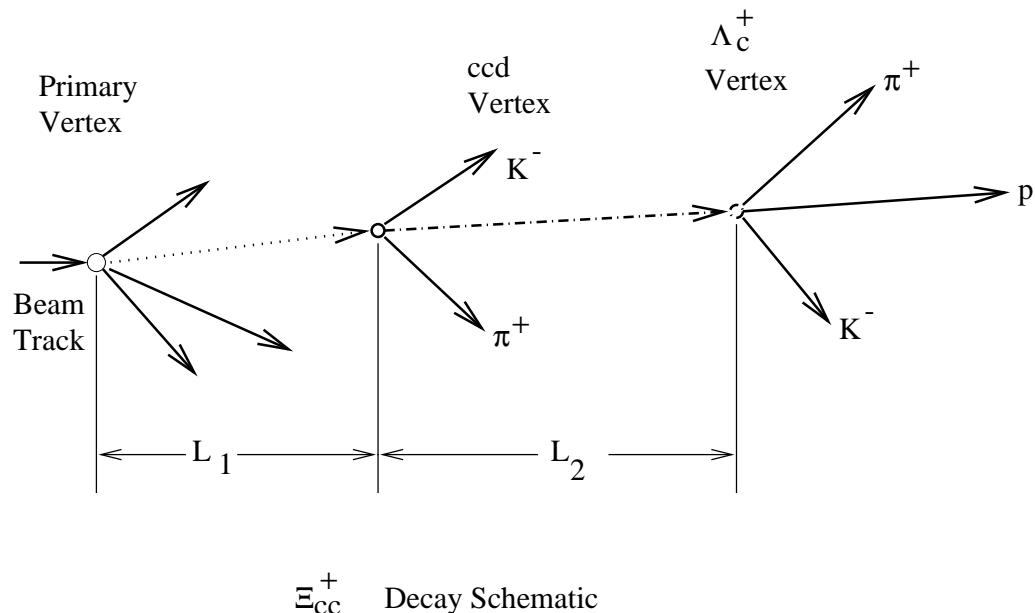
- PDG notation

	J	PDF	decay
ccd^+	1/2	Ξ_{cc}^+	$\Lambda_c^+ K^- \pi^+$
ccu^{++}	1/2	Ξ_{cc}^{++}	$\Lambda_c^+ K^- \pi^+ \pi^+$
ccu^{*++}	3/2	Ξ_{cc}^{++}	$\Lambda_c^+ K^- \pi^+ \pi^+$ and $ccd^+ \pi^+$

- Spectator Diagrams for $\Xi_{cc}(J=1/2)$ Decays

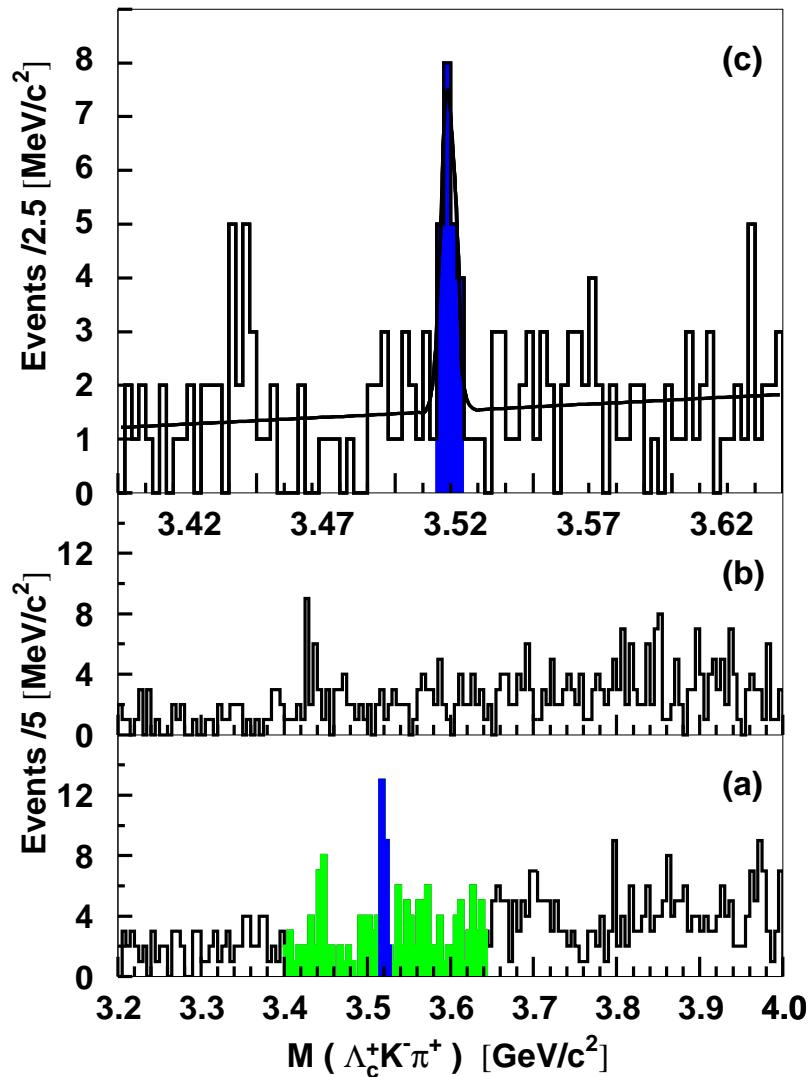


SELEX Double Charm Baryon Search Strategy



- ccq baryons can decay to cqq baryon
look for Λ_c^+ plus extra vertex of $L_1 < L_2(\Lambda_c^+)$
- Cabibbo-allowed: $c \rightarrow s + W^+$
require K^- (not K^+) at ccq vertex
- No RICH PID on tracks from ccq vertex (RICH threshold $p > 22$ GeV/c)
assign mass according to topology

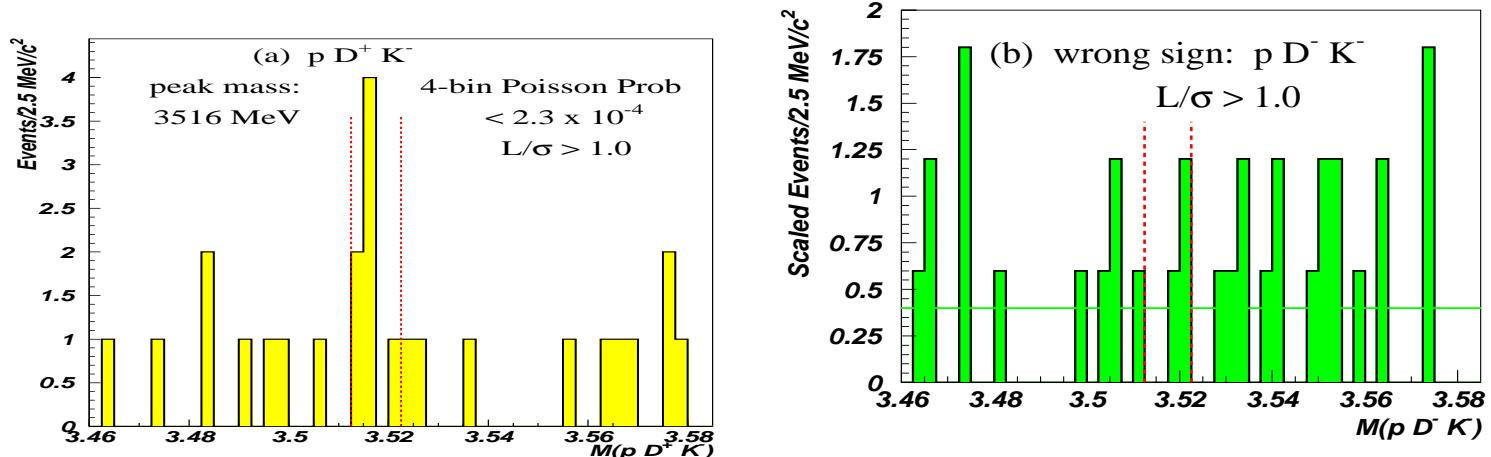
Observation of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ PRL 89 112001 (2002)



- $\Lambda_c^+ K^- \pi^+$ invariant mass
 - (a) Right-sign mass spectrum
 - (b) Wrong-sign mass spectrum
 - (c) Signal fit
- 15.9 events over 6.1 ± 0.5 events
Poisson prob. $< 1.0 \times 10^{-6}$
- Mass: $3519 \pm 2 \text{ MeV}/c^2$
- Lifetime: $\tau < 33 \text{ fs (90\% CL)}$
- $\langle p_T \rangle \sim 1 \text{ GeV}/c$ and $\langle x_F \rangle \sim 0.33$
- $\Xi_{cc}^+(3520)$

Confirmation of $\Xi_{cc}^+(3520)$ via pD^+K^-

Reconstruction RICH identified p and any K^- vertex $L < L(D^+)$



Excess 5.4 events over 1.6 ± 0.35 at 3518 ± 3 MeV/ c^2

- Production by Beam and Target: $\Lambda_c^+ K^- \pi^+$

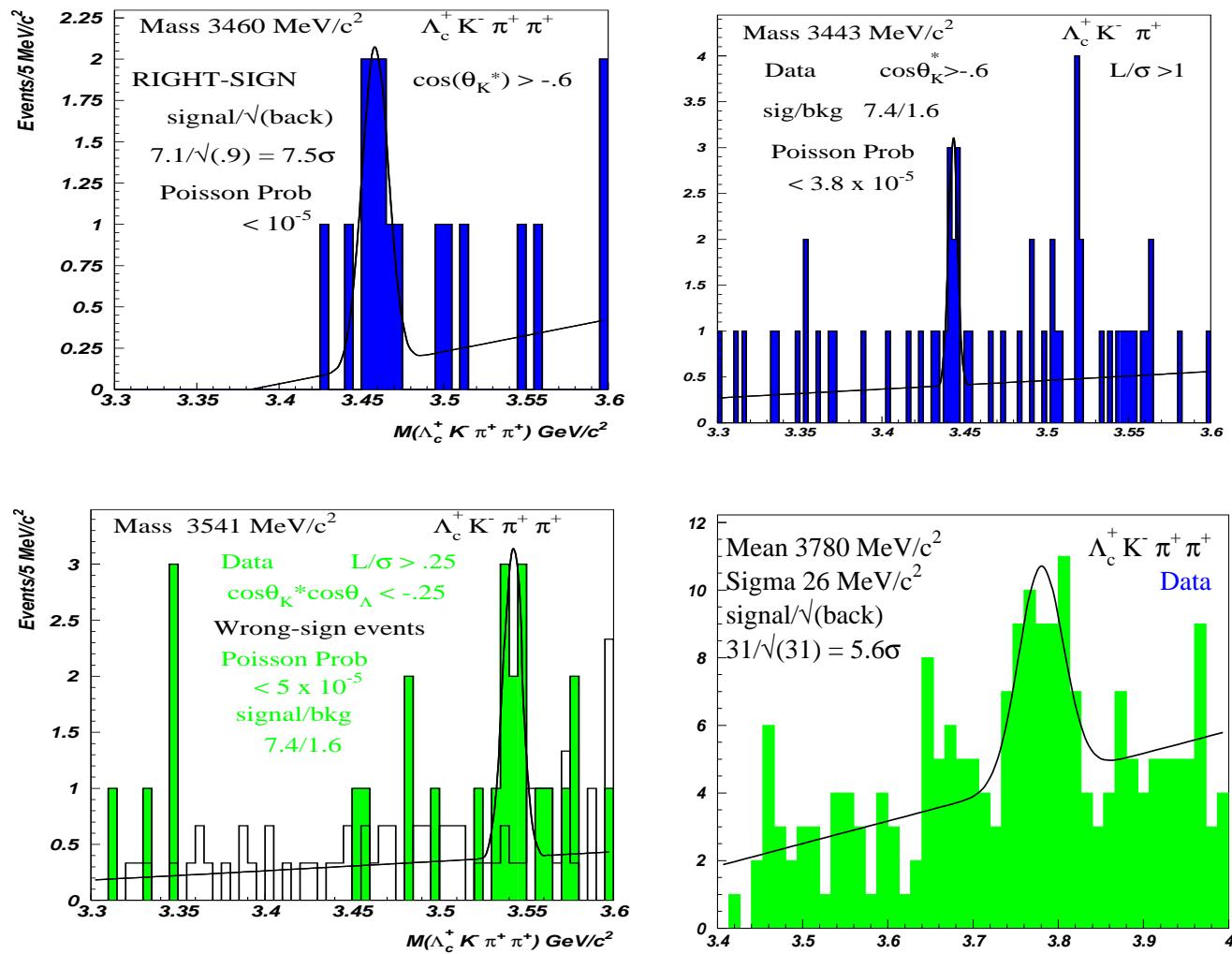
Beam/Target	Σ^-	proton	π^-	C	Cu
Interaction fraction	0.67	0.18	0.13	0.68	0.32
$ccu(3520)$ signal	18	4	0	18	4
$ccu(3520)$ sideband	110	21	7	93	47

Double charmed baryon candidates are produced solely by the baryon beams

- Λ_c economics: $\sim 20\%$ of SELEX Λ_c^+ produced by X_{cc}^+

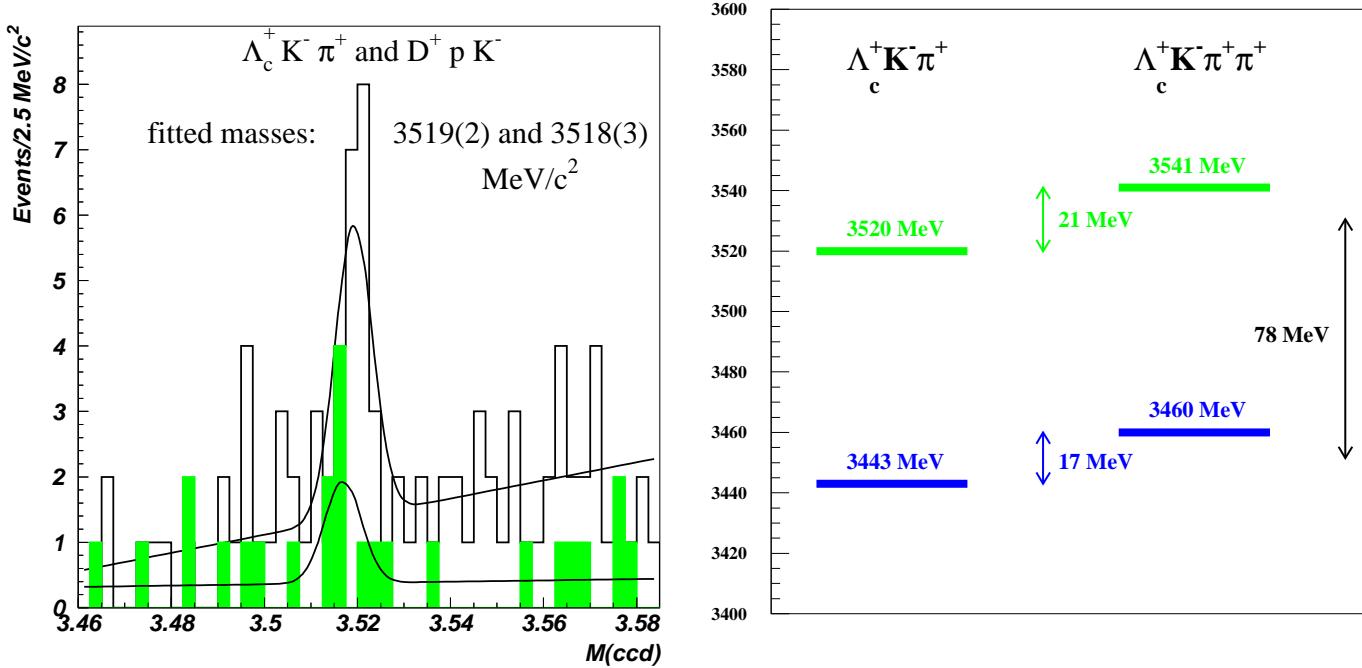
Other SELEX Double Charm Candidates

where is *ccd* partner, *ccu*?



Detail physics discussion for these states can be found at
<http://www-selex.fnal.gov/documentation/fNAL.pdf> (J.Russ)

Summary of Ξ_{cc} at SELEX



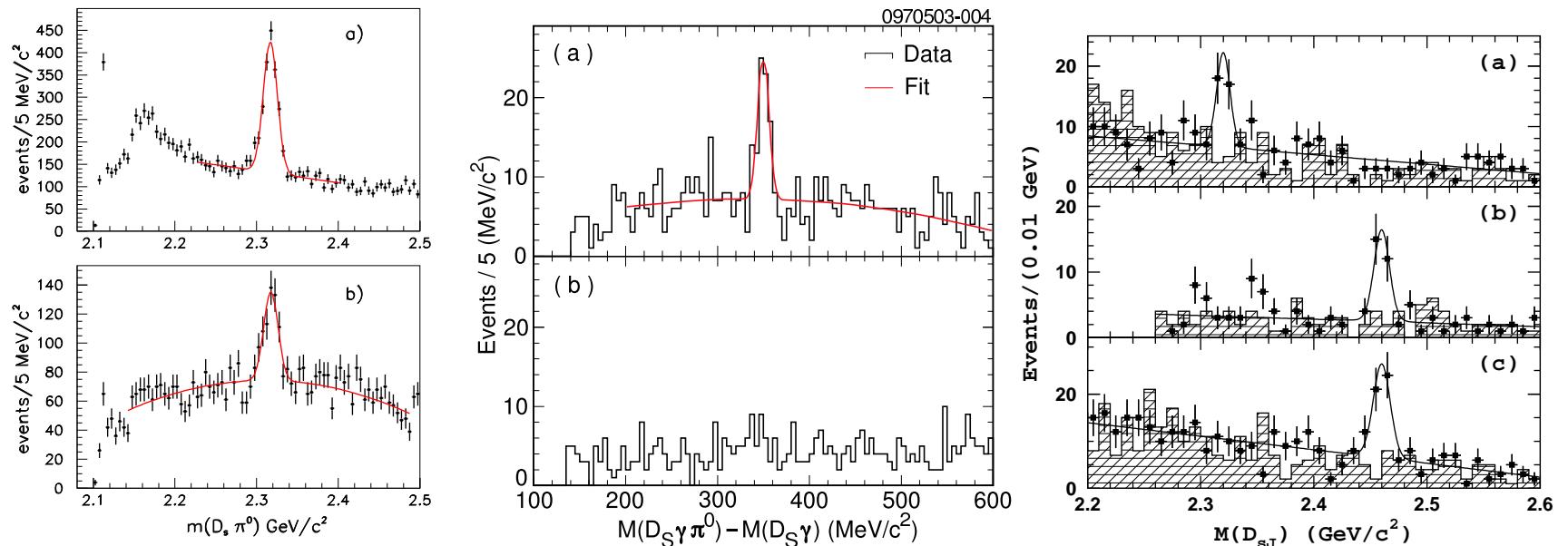
- Mass($X_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $pD^+ K^-$) = $3518.7 \pm 1.7 \text{ MeV}/c^2$

$$\frac{\Gamma(X_{cc}^+ \rightarrow pD^+ K^-)}{\Gamma(X_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)} = 0.078 \pm 0.045$$

- SELEX Double Charm Spectroscopy (Preliminary)

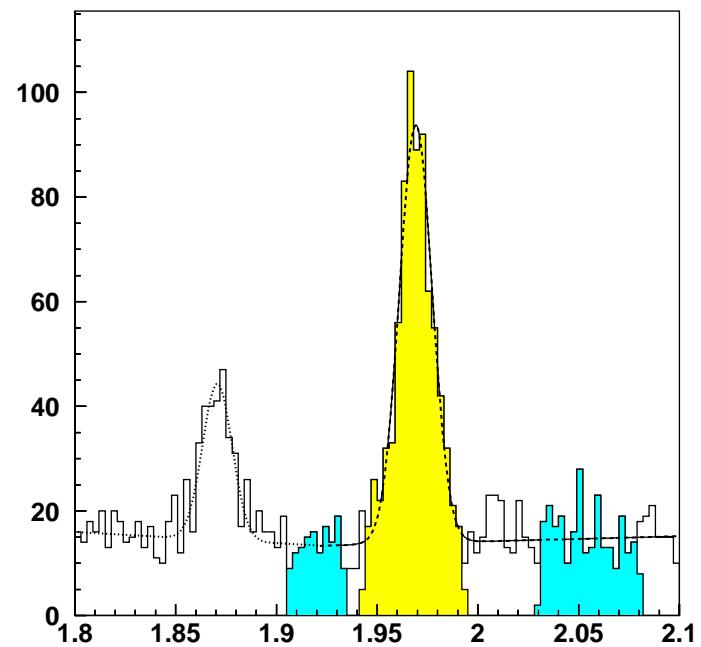
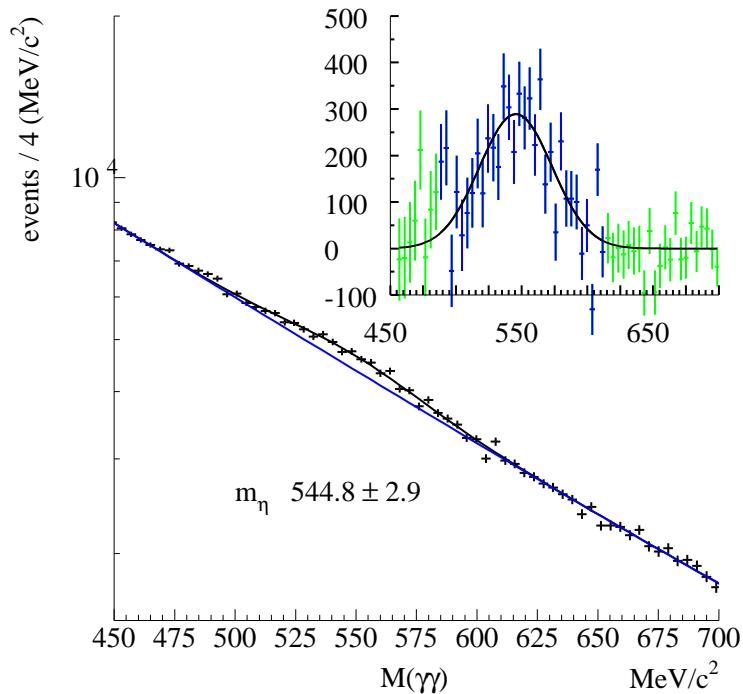
Heavy-Light Spectroscopy

- In 2003, $D_{sJ}(2317)$ by BaBar and confirmed by CLEO, BELLE unexpectedly low mass of the state below DK threshold



- Chiral model predict $D_s[0^+, 1^+] \approx D_s[0^-, 1^-] + m_N/3(\text{MeV})$
- $D_{sJ}(2417)$ as a partner to $D_{sJ}(2317)$ (CLEO,BELLE)
- Pattern of parity-doubled states continue to higher excitation?

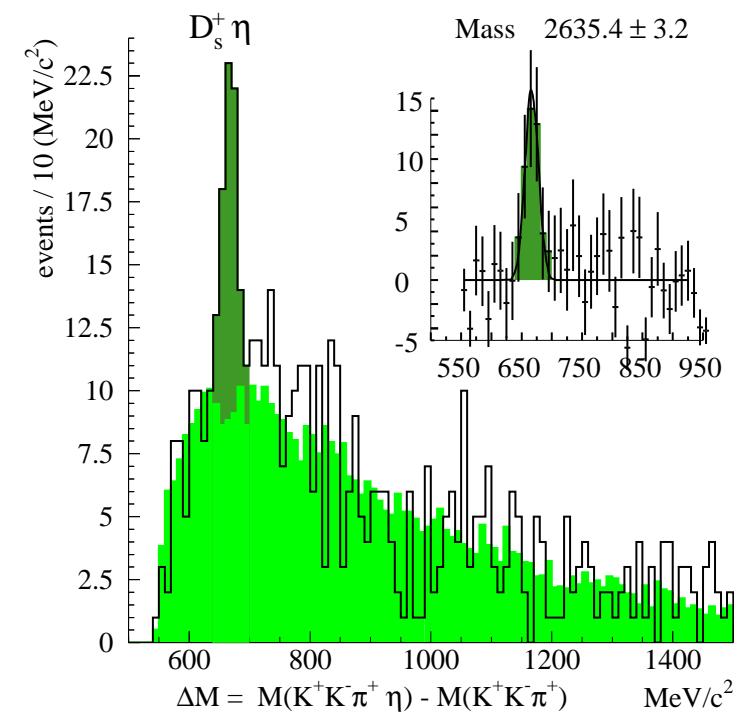
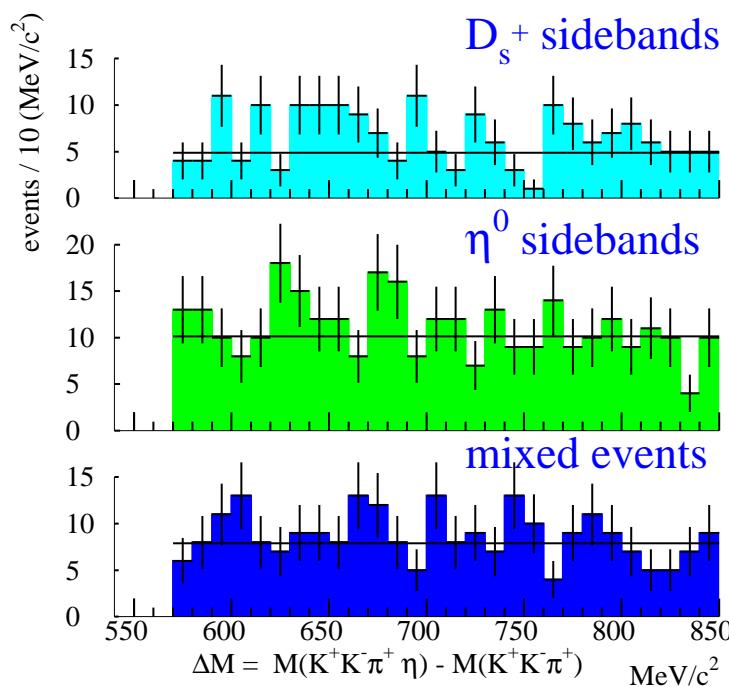
$D_s\eta$ Search: η and D_s Selection



- $E_\gamma > 2$ GeV and $N_\gamma \leq 20$
- $E_\eta > 15$ GeV and $N_\eta \leq 5$
- $D_s^\pm \rightarrow K^+K^-\pi^\pm$ signal sample used in for lifetime and production, but (554 ± 29) Σ^- induced signal events with a tighter π RICH PID cut.

Recipe for $D_s\eta$

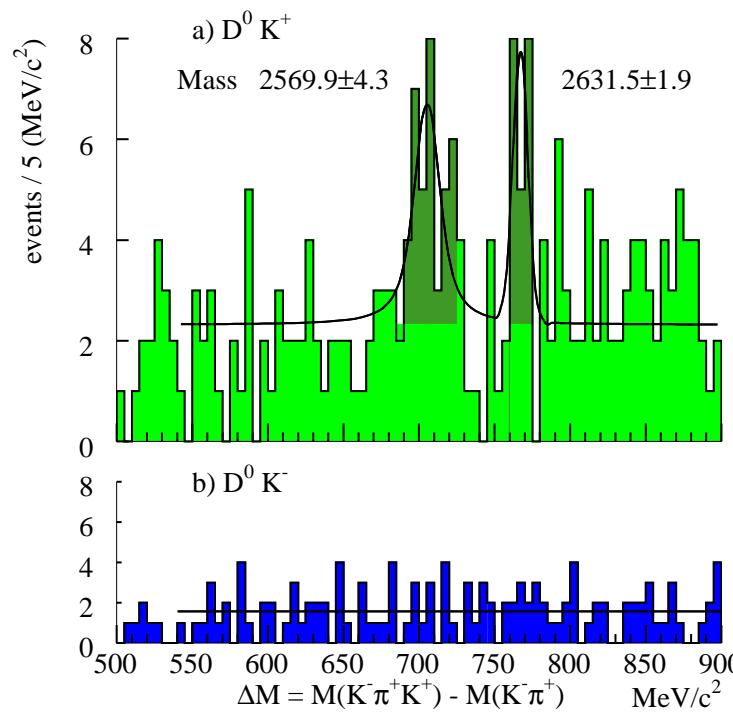
- Combined D_s with η candidates ($\sim 1.2\eta/D_s$)
- M_η constraint to PDF2002 and $p_\eta = [\vec{p}_{\gamma\gamma}, M_\eta]$
- Combinatorial background studies for $\Delta M = M(KK\pi\eta) - M(KK\pi)$



- 43.4 ± 9.1 signal events (6.2σ) at 2635.4 MeV/c²

$D_{sJ}^+(2632) \rightarrow D^0 K^+$ Search

- perform independent search for the kinematically allowed decay $D^0 K^+$
- Σ^- induced $D^0 \rightarrow K^- \pi^+$ and Strong RICH id on K^+
 $p(K) > 45 \text{ GeV}/c$ and $\text{Prob}(K)/\text{Prob}(\text{any}) > 10$



- 14.5 ± 4.5 events at $2631.5 \pm 1.9 \text{ MeV}/c^2$

Unusual Branching Ratio and Width

- Most models: $D^0 K^+$ coupling should be much bigger than $D_s^+ \eta$ for $c\bar{s}$
- Phase space favors $D^0 K^+$ mode by a factor 2.35
- SELEX sees $3\times$ as many $D_s^+ \eta$ decays as $D^0 K^+$

$$\frac{\Gamma(D^0 K^+)}{\Gamma(D_s^+ \eta)} = 0.16 \pm 0.06$$

- Width of $D^0 K^+ < 17 \text{ MeV}/c^2$ (90% CL)
- Not seen in b-factories, why is that?
- compare $D_s^*(2112)$ Production at CLEO

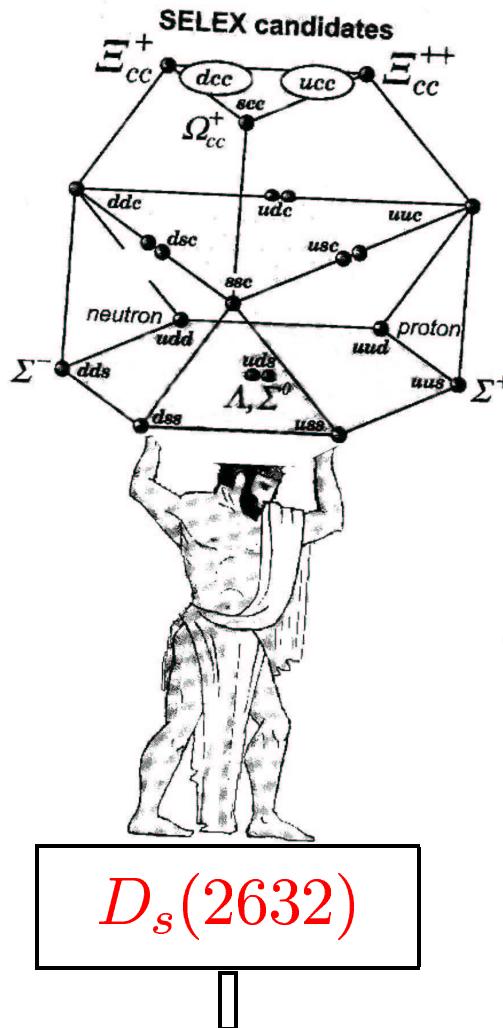
CLEO : $D_s^*(2112)/D_s = 0.59 \pm 0.03 \pm 0.01$

SELEX: $D_s^*(2112)/D_s = 0.24 \pm 0.06$

SELEX: $D_s^*(2112)/D_s = 0.53 \pm 0.13$ (after removing $D_s \eta$ contribution)

- new SELEX signal is not related to $D_s^*(2112)$ production

Summary and Perspective



- Both Ξ_{cc} and $D_{sJ}(2632)$ seen in two decay modes
- Confirmations from others will call theorists on vacation
- SELEX looking for $D^0 p K^- \pi^+$, $\Xi_c^+ \pi^+ \pi^- (\pi^+)$
- SELEX also looking for $\Omega_{cc}^+ \rightarrow \Xi_c^+ K^+ \pi^-$
- Can SELEX complete the 20-plet with SU(3) octet?